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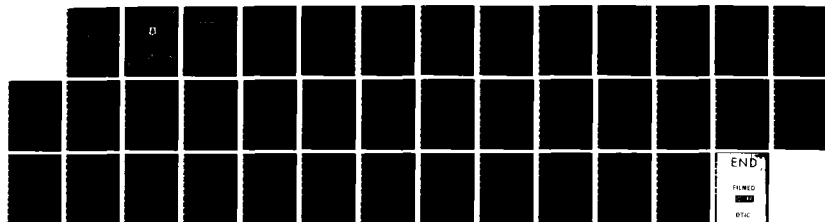
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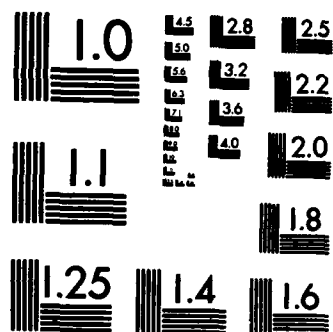
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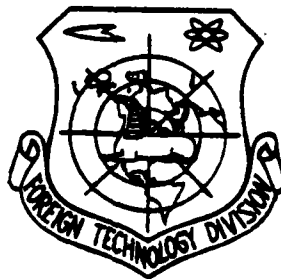
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FIBER-OPTIC COMMUNICATIONS SYSTEMS

by

M. Cvijetic and N. Savic



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FIBER-OPTIC COMMUNICATIONS SYSTEMS

by Milorad Cvijetic and Nikola Savic

Translator's note: Schema should read diagram.

Introduction

In the last few years a progress, which few had expected, has been noted in the field of fiber-optic information transmission. When in 1970 an optic fiber was produced with losses of 20 dB/km, it became clear that this concerned a transmission medium which possessed a series of advantages in comparison with classical cables. From then on progress in the field of optic fibers has been great. Data about optic fibers, whose attenuation approaches the theoretical limit (around .18 dB/km at wavelengths of around 1.3 μ m), can now be found in the literature.

Parallel to improvements in the technology of the production of optic fibers, great progress has also been made in the production of the other optical components, which enter into the composition of a system of fiber-optic information transmission. This is related, above all, to light sources and detectors. Today, semiconductor laser diodes are being produced, which operate in a continuous regime and have very good threshold current and linear characteristics, as well as an adequate operating period. This is also true of semiconductor photodiodes for which were achieved satisfactory sensitivity characteristics even for the wavelength region of around 1.3 μ m, which is especially interesting for transmission, because losses in a fiber are less in this wavelength region and even the total dispersion is minimal in an optic fiber.

Fiber-optic information transmission, as well as optical cable

transmission, has a group of advantages in comparison with classical cable transmission. These include:

- resistance to natural electromagnetic disturbances;
- the absence of the closed contours of communications between transmitter and receiver through the earth;
- the discreteness of information transmission;
- the absence of sparking and short circuits in the system;
- the small overall dimensions and mass of the device;
- the wide information transmission range;
- the possibility of the use of material more common than copper.

Fiber-optic information transmission systems are being used more and more for commercial purposes. Whether they will completely replace classical systems in those areas where it is possible will be determined not only by comparative technical advantages, but also by economic variables. However, time is totally on the side of fiber-optic transmission systems.

The broad application possibilities of these systems are determined by the advantages extended by them. The suitability of their use is especially seen in urban settings and for military purposes.

Before we move on to a description of the characteristics of these systems and their individual elements, as well as their application, we will present a short discussion of the basic principles of the channeling of light through an optic fiber as a medium for information transmission.

The Basic Principles of the Channeling of Light Through an Optic Fiber

The structure of the electromagnetic field in the optic fiber determines the characteristics of the fiber's impulse response. A large number of directed waves (modes) can be generally passed through the fiber. However, in certain cases, which are dictated by the optic fiber's structure only one directed mode can be passed through it. In accord with this, we can divide all fibers into single and multimode groups.

Multimode fibers also include fibers with a gradual and gradient refraction index depending upon whether the refraction index in the fiber's core is constant or varies according to some law. The general structure of the optic fiber is given in illustration 1. The fiber's internal part represents the core, and its external part is called the housing.



Illustration 1. An optic fiber

The majority of optic fibers with a gradual refraction index profile are produced so that the difference of the refraction index of the core and housing amounts to a few percent or even less, that is

$$n_1 = n_2 (1 + \Delta), \quad (1)$$

where:

n_1 --the core's refraction index;

n_2 --the housing's refraction index and $\Delta \ll 1$.

For fibers with a gradient refraction index, the refraction index varies approximately according to the following law:

$$n(r) = n(0) \cdot \left[1 - 2\Delta \cdot \left(\frac{r}{a} \right)^\alpha \right] \quad (2)$$

$\text{za } 0 < r \leq a, \alpha > 0$

$$n(r) = n(a) \text{ za } a < r,$$

where the exponent α can have different values, but the optimum profile, from the standpoint of the fiber's largest allowable volume, is obtained in the vicinity of the value $\alpha=2$.

The crack-crack model of the path of rays for a fiber with a gradual refraction index (illustration 2) can be adopted when considering the channeling of light through an optic fiber, while the path of rays in a fiber with a gradient index has the appearance shown in illustration 3. These fibers have the property of the periodic focusing of rays and the reduction of the difference of their paths through the optic fiber, which significantly increases the fiber's allowable volume, because the impulse dispersion is smaller.

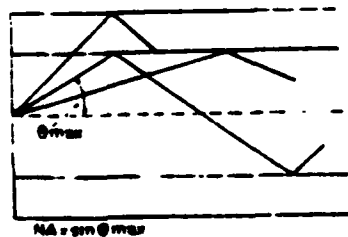


Illustration 2. The paths of rays in a fiber with a gradual refraction index

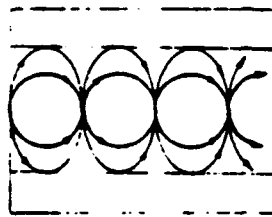


Illustration 3. The paths of rays in a fiber with a gradient refractive index

In order to understand the mode parameters which determine the fiber's characteristics, it is necessary to consider the Maxwell equations for the fields in a fiber with boundary conditions on the core-housing boundary.

The Maxwell equation, which describes the field in cylindrical coordinates, has the form:

$$\frac{d^2\psi}{dr^2} + \frac{1}{r} \frac{d\psi}{dr} + \frac{1}{r^2} \frac{d^2\psi}{d\varphi^2} + (k^2 - \beta^2) \psi = 0 \quad (3)$$

where:

r --the radius;

φ --the azimuth angle;

ψ --the wave function which describes the channeling of light;

k --the wave vector, and

β --the channeling constant or the component of the wave vector in the direction of the z -axis.

Assuming that the wave function has the following form:

$$\psi = A \cdot F(r) e^{i\varphi} \quad (4)$$

and with the separation of the variables in equation (3), the following differential equations are arrived at:

$$\frac{d^2 F(r)}{dr^2} + \frac{1}{r} \cdot \frac{d}{dr} F(r) + \left[k^2(r) - \beta^2 - \frac{v^2}{r^2} \right] \cdot F(r) = 0. \quad (5)$$

In the case of a fiber with a gradual index, equation (5) obtains the form of the Bessel equation. Keeping in mind the boundary conditions that the field has a finite value on the fiber's axis ($r=0$) and that it disappears for $r \rightarrow \infty$ for the field's vertical component, the equation can be written in the following form:

$$E_z = \begin{cases} A J_0 \left(\frac{ur}{a} \right) \cdot e^{i v \theta}, & r \leq a \\ B K_0 \left(\frac{wr}{a} \right) \cdot e^{i v \theta}, & r > a. \end{cases} \quad (6)$$

$$\text{gde je: } u^2 = (k^2 - \beta^2) a^2,$$

$$k = \frac{2\pi n_1}{\lambda_0}, \quad w^2 = (\beta^2 - k_2^2) a^2, \quad k_2 = \frac{2\pi n_2}{\lambda_0}.$$

It is necessary to observe that $w^2 + u^2 = \left(\frac{2\pi a}{\lambda_0} \right)^2 (n_1^2 - n_2^2)$, is the constant size for all modes and represents the fiber's characteristic. Parameter V must be used in determining the number of modes and can be approximately tied to the fiber's angle of reception and the dispersion in the fiber. For the main modes the mode vector in core "u" is realistic thus leading to oscillatory solutions for equation (5).

The inherent solutions for u and w can be found when the boundary conditions are applied in relation (6). For $v=0$ the polarized TE and TM modes, which are radially symmetrical, are obtained. For $v \neq 0$

modes are no longer simple TE and TM modes, but represent hybrid modes, which have all three field components and are designated by HE_{mn} ($m \neq v$) and EH_{mn} depending on whether the magnetic or electric component is dominate.

In the case of fibers with a gradient index, differential equation (5) can be approximately solved by aid of the Hermite-Gauss function. The modes' characteristic in this case, although more complex, is considered to be the same as with fibers with a gradual index.

In order to channel only one mode through a fiber, the core's diameter must be on the order of the several wavelengths of light, which spread through it, and the fiber must have a sufficiently small difference between its core and housing refraction indexes. In the case when V is less than 2.405 only one mode designated as HE_{11} is channeled through the optic fiber.

The use of single mode optic fibers provides considerable advantages in view of the fiber's transmission capacity. However, there exist many difficulties connected to its production and exploitation, as well as to the introduction of light into it.

The number of modes, which are channeled through an optic fiber, increases with an increase in parameter V . In the first approximation it can be taken that the number of modes in a fiber with a gradual refraction index is given as:

$$N \sim \frac{V^2}{2} \quad (7)$$

For a large number of modes the channeling of light in a fiber can be

well described as stemming from the principles of geometric optics and the theory of light rays. The maximum angle, which encloses the ray with the optic fiber's axis at the fiber's entrance and which can be spread through the fiber, is defined as the angle of the total reflection at the core-housing boundary. Today, the concept of numerical openness (apertures) is widely used in calculating the power which is inserted into the optic fiber and the efficiency of source's joining with the fiber. The numerical openness for a fiber with a gradual index is defined as:

$$NA = \sin \theta_{\max} = (n_1^2 - n_2^2)^{1/2} \approx n_1 \sqrt{2\Delta}, \quad (8)$$

where θ_{\max} -- the maximum angle of light reception (illustration 2).

The above expression defines the external numerical openness for an optic fiber. The internal numerical openness describes the critical angle at the core-housing boundary and is given as $\sqrt{2\Delta}$.

For optical fibers with a gradient refraction index the situation is more complex. In this case the numerical openness is a function of the radial distance from the axis. The ray, which falls at a radial distance of r from the axis, falls on a radial axis in the form of a main mode only if it is found inside of the local numerical openness $NA(r)$ for that point. The local numerical openness is defined as

$$NA(r) = NA(a) \cdot \sqrt{1 - \left(\frac{r}{a}\right)^{2\alpha}}, \quad (9)$$

where:

a -- the radius of the fiber's core;

α -- the exponent which is defined in relation (2).

The number of modes, which can be channeled through a fiber with a

gradient index is determined by the expression given by Gloga as:

Two times more modes in comparison with fibers which have a gradient refraction index ($a=2$) and the same value for Δ can be channeled through an optic fiber with a gradual index and the given Δ .

The Structure of a Fiber-Optic System for Data Transmission

According to the configuration of the structural schemas of this system for data transmission we can conditionally divide them into four types: a) vertically open, b) closed contour, c) radial, d) net.

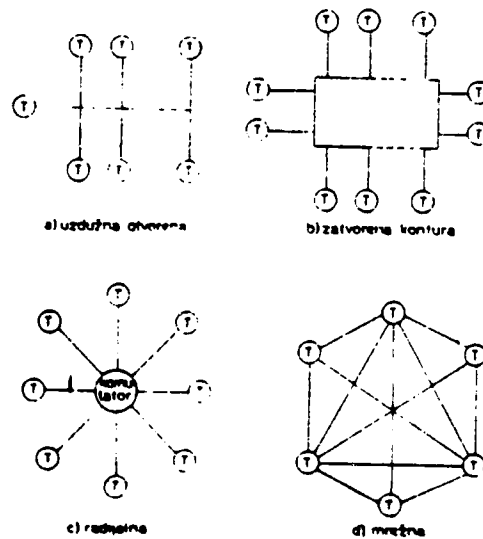


Illustration 4. The structural schemas for data transmission
a) vertically open, b) closed contour, c) radial, d) net, 1. commutator

The first two structural schemas, as in illustrations 4a and 4b, provide the systems with the shortest length and the simplest terminal attaching. However, with the need to increase the number of

terminals grows the demand for an increase in the transmitter's optical power, and an inequality of its distribution appears in the structural schemas of type a) and b). Because of this the receiver must have a wide dynamic range for amplification regulation in order to be able to receive both very strong and very weak signals. Moreover, it is necessary that noise be reduced to the minimum in the terminals' electronic parts.

The drawback of structural schemas a) and b) is a small capacity because of the serial transmission of data from user to user.

The radial structure of a fiber-optic system for data transmission (illustration 4c) represents a parallel type scheme. It must be used with a large number of terminals and with communication systems of the smallest possible lengths. Differently from serial structures (as with a) and b)) for which with an increase in the number of terminals the total loss of light power grows very rapidly, with parallel structures this increase of loss proceeds slowly.

The common element for all terminals, which appear with radial structures, is a device for data exchange, which commutes the communication channels between users.

The system using the net structure (illustration 4d) is suitable for application chiefly with a small number of terminals in a communications system. This type is differentiated by its great operating speed, security and maximum utilization of the energy emitted by the optical transmitter. A break in the connection between two terminals here will not result in the entire system's going down, since with the modification of the system's structure the direction of the data's transmission can be changed and the

interrupted connection by-passed. The essential drawback of net structures is the large number of optical communications lines.

The composition of the structural schemas for fiber-optic data transmission systems is given in illustration 5; these can be divided here into three groups of elements:

- optical communications lines (reception and transmission modules and optical cables which are composed of many optic fibers);
- devices for data exchange (devices for control and optic commutators);
- final devices (terminals).

We will now turn our attention to the basic elements for the sending, transmission and reception of optical signals. These are optical sources, optical cables and optical detectors. We will also consider some principal schemas for an optical transmitter and receiver, as well as an optical signal regenerator.

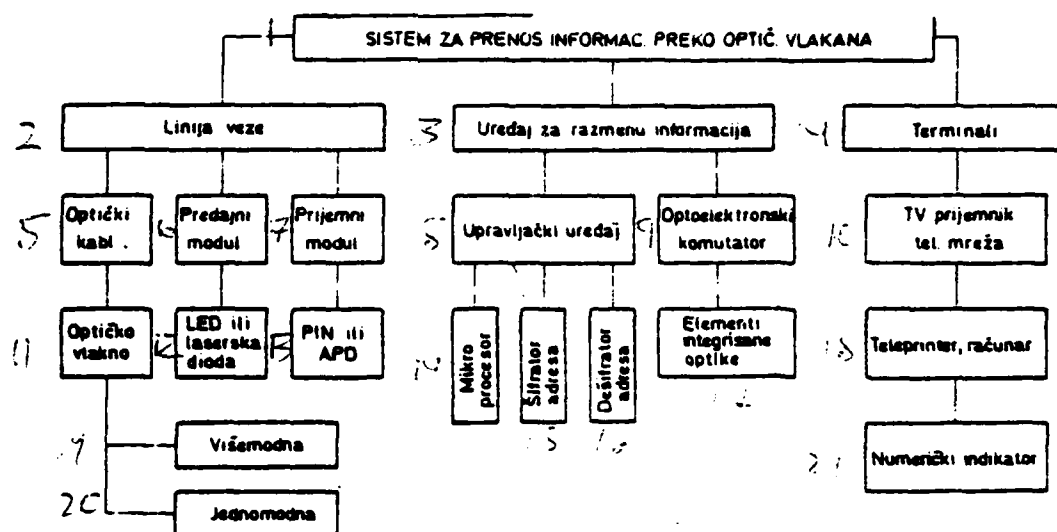


Illustration 5. The composition of a structural schema of a fiber-optics data transmission system

1. the fiber-optics data transmission system, 2. connection lines, 3. the device for data exchange, 4. terminals, 5. optical cable, 6. transmission module, 7. reception module, 8. control device, 9. optoelectronic commutator, 10. TV receiver, tel. network, 11. optic fiber, 12. LED or laser diode, 13. PIN or APD, 14. microprocessor, 15. address coder, 16. address decoder, 17. integrated optics elements, 18. teleprinter, computer, 19. multimode, 20. single mode, 21. numerical indicator

Sources of Optical Emission

It is necessary to take into account the following requirements when selecting an optical emission source:

--the source must emit on a wavelength in which the losses in the optic fiber are the least;

--it must be possible to perform the rapid modulation of the light emission;

--the source must be compatible with the optic fiber in order to accomplish the most efficient source-fiber connection possible, while realizing the minimum loss in this connection;

--the source must have the smallest possible mass, overall dimensions and power necessary for its operation.

Such semiconductor light-emitting diodes and semiconductor lasers as Nd:YAG lasers fully satisfy these conditions. We will now consider some of the basic characteristics of these sources.

Light-Emitting Diodes (LED)

The optical emission of semiconductor light-emitting diodes (LED)

stems from the spontaneous recombination of the carriers of the charges injected through the p-n junction when current is flowing through it. In this way, the principle of the functioning of light-emitting diodes itself permits the amplitudinal modulation of emission by means of the feed current. However, the light-emitting diodes have a limited operating speed, which is determined by the time of the spontaneous recombination of the carriers and the capacitance of the p-n junction, and can permit the transmission of data at speeds up to 100 Mbit/s.

Emission at the exit of these diodes is incoherent and contains a large number of spatial modes. Therefore, it is necessary to use a multimode optic fiber with a large numerical openness in order to efficiently transmit energy to the optic fiber.

Both light-emitting diodes, as well as semiconductor lasers, are made on the basis of semiconductor material of the third and fourth order. The increase of the exiting optical power with light-emitting diodes can be achieved by producing an area of a double heterostructure. This area is usually created by the insertion of a thin active area (p-GaAs) between two layers of GaAlAs, as is similar to lasers (illustration 7).

Light-emitting diodes have an active surface on the order of $2 \times 10^{-5} \text{ cm}^2$ and a light emission density of $100 \text{ W/sr} \times \text{cm}^2$ for a direct current of 150 mA. The width of the emission spectrum is around 30-40 nm, and the external quantum effectiveness is 2-3 percent. The typical modulation characteristic, that is, the dependence of the exiting optical power on the current through the diode is given in illustration 6.

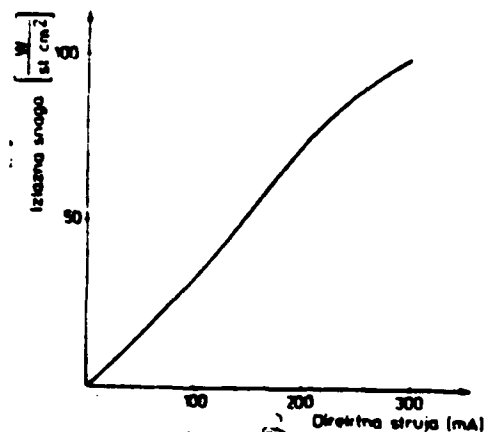


Illustration 6. The dependence of the exiting power on the direct current of the light-emitting diode
1. exiting power, 2. direct current

The optical power which the diode transmits to the optic fiber is given by the relation:

$$P = B_s \cdot A_s \cdot \theta = B_s \cdot A_s \cdot [\pi(NA)^2] = 2\pi B_s A_s n^2 \Delta \quad (11)$$

where: B_s --the exiting radiated source; A_s --the active surface of the source or the surface of the fiber's core depending on which is less; θ --the fiber's angle of reception.

The losses at the source-fiber connection for typical optical fibers with a small numerical openness (4-1 percent) amount to around -16 dB when a LED serves as the light source. For optic fibers with a gradient index the losses at the connection with the source are greater by 3 dB. The reasons for this were cited earlier.

The modulation of the emission of light-emitting diodes is created by the modification of the direct current running through them. The appearance of the modulation characteristic for individual harmonic components is similar to illustration 6. The exiting optical power

of the LED depending on the modulation frequency is given as:

$$\frac{P(\omega)}{P(0)} = \frac{1}{[1 + (\omega\tau)^2]^{1/2}} \quad (12)$$

where: ω --the modulation frequency; τ --the recombination time in the active area.

Light-emitting diodes, which are today produced and have a lateral emission, have a "3 dB modulation range" around 200 MHz.

Semiconductor Lasers

Semiconductor injection lasers are the most effective sources used in fiber-optics communications systems. They, like light-emitting diodes, make possible direct modulation by the feed current, and the speed of their operation is determined by the time of the stimulated emission and the time of the photon's life. So, for example, for injection lasers based on the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterojunction, the functioning's speed is determined as 10^{-11} - 10^{-10} s.

These lasers, moreover, have a significantly greater efficiency and a smaller aperture emission angle which allows the majority of the laser's emission to be injected into the optic fiber.

The laser emission arises with currents, which are greater than that of the laser's threshold. Semiconductor lasers with small threshold currents (around 50 mA) and which emit in a continuous regime (CW lasers) are obtained with modern technological procedures. The corresponding density of current for this amounts to around 10

A/cm³.

The large densities of the working currents, as well as the laser structures' imperfections, which appear in the production process, are the causes of the heterojunction's "catastrophic degradations" and the limitation of the laser's working life.

The structure of one semiconductor laser with heterojunctions is given in illustration 7.

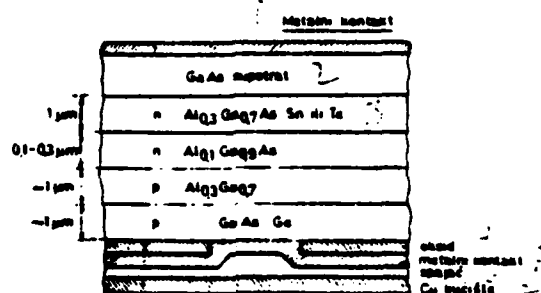


Illustration 7. The structure of a semiconductor laser
1. metal contact, 2. substrata, 3. or, 4. oxide, 5. metal contact, 6. connector, 7. Cu housing

The basic advantages which the use of semiconductor lasers provides in relation to LEDs are: a) a greater operating speed, which makes possible the transmission of digital data at rates up to several Gbit/s; b) a greater initial power which is given the optic fiber; c) a smaller emission spectral width of around 2 nm, which effects the increase of the system's data capacity. The following can be stressed as the drawbacks of lasers: a smaller linear modulation characteristic in relation to the LED, a shorter working life and higher cost.

Of the other sources, which can be used in a fiber-optics data transmission system, mention must be made of superluminescent diodes and YaG:Nd lasers.

Light generation with superluminescent diodes is conditioned as both a spontaneous and a stimulated emission. The operating speed, therefore, of these diodes reaches 10^{-9} s, and their emission spectral width amounts to around 10 nm. According to their characteristics these diodes stand at the transition between the LED and semiconductor lasers, and can transmit data at speeds up to several hundred Mbit/s.

YaG:Nd lasers emit light at a wavelength of $\lambda = 1.06 \mu\text{m}$. Direct modulation cannot be accomplished with them, and therefore, they require an external modulator. However, progress, achieved in recent years in the field of the modulation and commutation of optical emission, makes possible the utilization of these solid state lasers in fiber-optics communications systems.

Optical Emission Detectors

Optical emission detectors, which are used in fiber-optics communication systems, must satisfy defined requirements, including: great sensitivity, sufficiently rapid operating speeds, operating characteristics independent of external conditions and which are compatible with optic fibers and electronic devices.

The mentioned requirements are best met by semiconductor photodiodes. These are divided into so-called p-i-n photodiodes and avalanche diodes, which besides the mentioned characteristics are small in size and operate on a relatively small feed voltage. We will provide here

a short description of some of the properties of these photodiodes.

P-I-N Photodiodes

The structure of these photodiodes is given in illustration 8. In the same illustration is presented the distribution of the electrical field along the the length of the diode's structure. It is seen that one n layer, which is weakly contacted and which makes an "i" region, is added to the classic p-n structure. In this way a self-conductive region is placed between the two semiconductor regions of opposite conductivity. With sufficiently large inverse voltages the electrical field is arranged as has already been shown in illustration 8. Since the i-region can be sufficiently wide, more sensitive and faster photoreceivers can be produced on the basis of such photodiode structures. The free carriers, which are created with the absorption of photons in the i-region are accelerated by the electrical field toward the junction. Therefore, if the inverse voltage in the structure is sufficiently great, the free carriers will reach the speed of thermal motion; the diode's temporal constant is determined by the time of the carrier's passage through its own region:

$$\tau = \frac{b}{v_t} \quad (13)$$

where: b --the width of the i-region; v_t --the speed of the carrier's thermal motion.

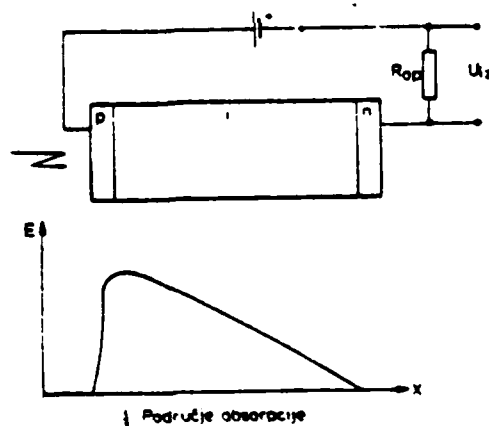


Illustration 8. A p-i-n photodiode
1. the absorption region

The capacitance of the p-i-n structure is

$$C = \frac{S \cdot \epsilon_0}{b} \quad (14)$$

where: S --the junction's surface; ϵ_0 --the dielectric constant.

The capacity C can be reduced to a sufficiently small amount by reducing the width of b .

As with others, p-i-n diodes are characterized by the magnitude of their quantum effectiveness and minimum sensitivity. With the better p-i-n photodiodes are produced today, the quantum effect amounts to .5-.85 and the sensitivity .4-.6 A/W. The other parameters, which characterize p-i-n photodiodes, fluctuate around the following values: maximum working frequency--1 GHz, working

voltage--15-90 V, capacity--2-15 pF, etc.

So-called p-i-n/FET photodiodes with built-in preamplification on the basis of a FET transistor are being produced today. These have an amplification close to that of avalanche photodiodes, but with a significantly smaller working voltage and without the specific requirements in the stability of the working voltage.

Avalanche Photodiodes

If we take into account that the most sensitive photoreceivers work at a level of initial optical power on the order of a nanowatt and that the sensitivity of a p-i-n photodiode is around .5A/W, it follows that a current of several nanoamperes will be flowing through the diode. The obtained current signal must, then, be amplified by electronic methods, by which additional noise will also be introduced. Amplification with avalanche photodiodes takes place by means of an avalanche mechanism.

The structure of avalanche photodiodes is given in illustration 9. At a relatively high inversion voltage in the photodiode, the carriers, which pass through part of the i-region, can create new carriers by means of an impact ionization mechanism. This is the same phenomenon which results in the avalanche breakthrough with common diodes with inverse polarization. The newly created carriers can now create additional new carriers by means of the same impact ionization mechanism.

In this way the primary electron-cavity pair can lead to the formation of tens, hundreds or even more secondary pairs. The effective amplification of the avalanche diode is obtained as a result.

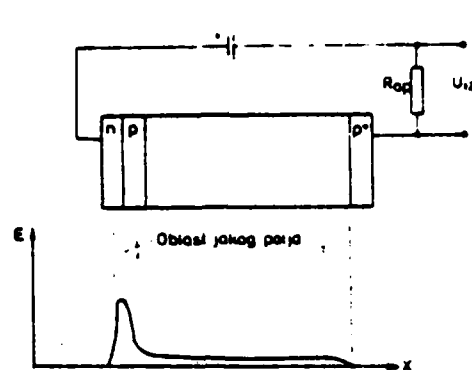


Illustration 9. The avalanche photodiode
1. the strong field region

With avalanche photodiodes, which are now being produced, the product of the current amplification and the frequency band can be around 100 GHz. However, in order to obtain larger coefficients of the current's amplification it is necessary to produce very high quality p-n junctions, which secure the homogeneity of the avalanche process and exclude the appearance of microplasmatic parts in the structure. Germanium and silicon are the most suitable materials for the production of avalanche photodiodes, as well as for p-i-n photodiodes.

The shortcomings of avalanche photodiodes in relation to p-i-n photodiodes are the temperature instability of the coefficient of the photocurrent amplification and the great demands on the stability of the feed's source.

Optical Cables

In order for optic fibers to be utilized practically, their

"cablization" is usually performed. An optical cable can contain one or many optic fibers, and can have different design performances. The design of an optical cable is chosen after a detailed consideration of its further application. The optical cable used for an optical communications system must satisfy the following requirements: the adequate protection against pressure which can cause an additional loss in the optic fibers; great resistance to strain, resistance to the penetration of water and moisture; temperature stability even above working temperatures; flexibility with regard to bending in cold weather; chemical resistance and resistance to being struck; easy laying and installation; acceptable cost.

A great number of optical cable designs have been proposed. Simple bundles of optic fibers with great numerical openness and large losses, optical cables with fibers which have fewer losses and contain strengthening elements, optical cables in the form of bands, etc. have received the greatest interest.

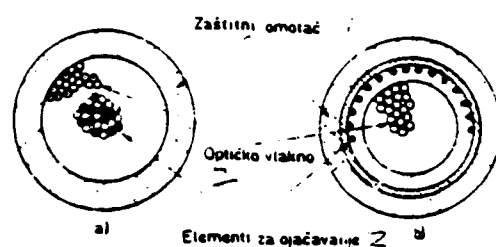


Illustration 10. The design of an optical cable with a central and peripheral distribution of strengthening elements

a) an optical cable with a central distribution of elements; b) an optical cable with a peripheral distribution of elements.

1. protective cover, 2. optic fiber, 3. strengthening elements

Two basic cylindrical designs for optical cables with a central and

peripheral position for strengthening elements are presented in illustration 10. The strengthening elements protect the optical cable from overstretching, and with the design shown in illustration 10b is one of axial twisting.

The band shaped optical cable is shown in illustration 11. These cables have an increased strength and great resistance to bending in one plane. However, when working with it, great care must be given to the cable's bending in the other plane.

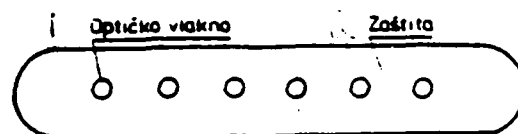


Illustration 11. A band shaped optical cable
1. the optic fiber, 2. the protection

Joining the Elements of Optical Communication

With a fiber-optics and optical cable data transmission system great care must be given to the joining and continuing of the individual elements. The following are related to the joining: the emission source--optic fiber, the optic fiber--emission detector, as well as the mutual joining of optic fibers.

Because of the irreconcilability of the geometrical characteristics of the emission source and the optic fiber, as well as their optical characteristics, the losses at the source-fiber connection are quite

large. This can be reduced by different design performances. The joining of the light source with the optic fiber has received great attention, as has the design of the optical connectors, which would permit the most efficient possible introduction of light into the fiber.

Fiber-fiber type connections can be classified in two groups: separable and inseparable. Separable connections are created by aid of a connector for the optic fibers. The separating and joining of the fibers in this way represent a normal use procedure. The contemporary designs of optical connectors for the creation of separable connections lead to additional losses in the line of around 1 dB per connection. Inseparable connections must be used when an undesired break appears in the optical fibers or even in entire cables. Before joining it is necessary to carefully work the fibers' ends in order not to create additional losses due to diffusion because of the unequal frontal surfaces of the fiber parts which are connected. Several procedures exist, which are efficiently utilized with this joining, from electric arc welding to the insertion of special resins and polymers between the ends which are joined. Presently, it has become possible to reduce the losses in one such connection to .2 dB.

The joining of fibers with light detectors is similar to that of the source and the fiber, but here the losses at the connection are significantly less because of the greater compatibility of the optic fiber-light detector connection. The losses at the fiber-detector connection go up to 2 dB.

The Reception-Transmission Modules in Fiber-Optics Communications Systems

The schema of a transmission and reception module is given in illustration 12.

The modulation of the emission of a laser or light-emitting diode with an initial electrical signal which carries the data is performed in the optical transmitter. This means that the modulation of the optical emission is direct. It is understood here that the initial electrical signal is already in a suitable form (a code, level), which is achieved by an entry adaptation device where necessary.

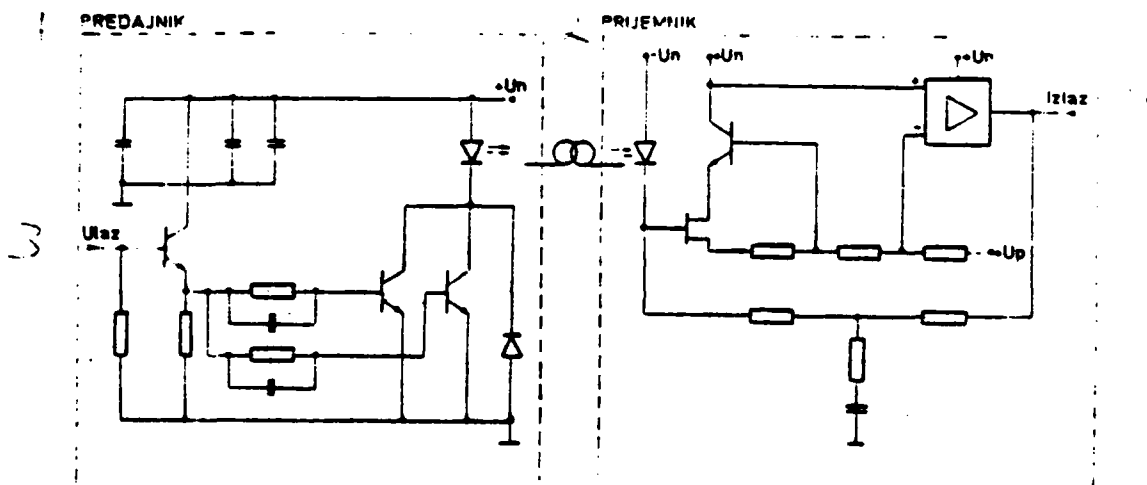


Illustration 12. The schema of the optical transmission and reception module

1. transmitter, 2. receiver, 3. entrance, 4. exit

The photocurrent creates some fall in the voltage in the load resistance in the optical receiver. This voltage is then further amplified. The reception amplifier must have a small inherent noise level and a large dynamic diapason. Usually, an amplifier with reverse reaction, which is composed of a preamplifier and wide band amplifier, is used. The amplifier's exit signal is proportionate to

the photocurrent.

It must be mentioned that a certain difference exists with the performance of the optical transmission and reception modules for analog and digital transmission. However, in principle, the process of the electrical conversion into optical signals and back runs in the same way. We will devote some attention here to the digital signal transmission modules, for which it is necessary to keep in mind the prior warning.

The reception photodiode is attached to the electrical circuit as is shown in illustration 13.

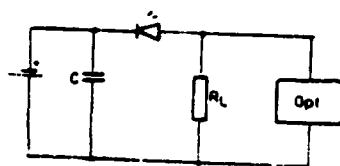


Illustration 13. A schema of the attachment of the photodiode

The feed source is regularly attached with the diode and load circuit. The load circuit is usually composed of high value resistance and alternating current amplifier, which is attached parallelly to it.

The estimation of the optimal amplifier is based on a series of practical factors, to which attention is carefully paid, while fundamental consideration is given to the amplifier's noise.

The photodiode's circuit can be represented by an equivalent schema

(illustration 14), where the photodiode is presented as the current source which is connected parallelly with its own capacitance and regularly with its own resistance.

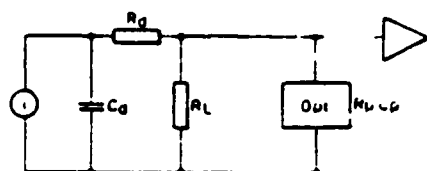


Illustration 14. An equivalent schema of a photodiode

A less than optimal amplifier (from the point of view of noise) can be represented in a type of parallel connection of the resistance and capacity after which comes the ideal amplifier with infinite impedance. If an amplifier has an amplification of $A(f)$, where f —the frequency within the boundaries of the band of the modulated frequencies, then the exit voltage of the frequency f , conditioned by the component of the current from the photodetector at frequency f , is determined by the simple relation:

$$U(f) = I(f) \cdot Z(f) \cdot A(f), \quad (15)$$

where $Z(f)$ is the load impedance at frequency f and that amounts to:

where
$$Z(f) = \frac{1}{1/R_s + j2\pi f \cdot C_s}, \quad (16)$$

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$$C_s = C_d + C_p; \quad R_s = \frac{1}{1/R_d + 1/R_p}. \quad (17)$$

If the optical power which falls on the photodetector is equal to $p(t)$ [W] and if the detector's sensitivity is B [A/W], then the voltage at

the amplifier's exit is determined as:

$$u(t) = p(t) \times B * h_1(t) * h_2(t), \quad (18)$$

where 9^* designates the convolution of the impulse characteristics: h_1 --the impulse characteristic of the detector, h_2 --the impulse characteristic of the the load and amplifier.

It must be kept in mind that the optical power used $p(t)$ changes in time with the speed which is determined by the band of modulated frequencies (in harmony with the modulation), and not with the optical frequency.

If, for example, the power $p(t)$ changes sinusoidally with an amplitude of $1 \mu W$ and a frequency of $1 MHz$, and if the detector's sensitivity is equal to $1 A/W$, and the amplitudinal phase characteristic of the amplifying part is equal to the unit for frequencies above $1 MHz$, the exit voltage will be $500 \mu V$ if the amplifier has an amplification of $20 dB$, and its entrance impedance in these frequencies is defined as the value of the load resistance R_L (50Ω). It is clear that this signal must be further processed and amplified. Let's consider an example of the structural schema of a digital receiver of an optical signal.

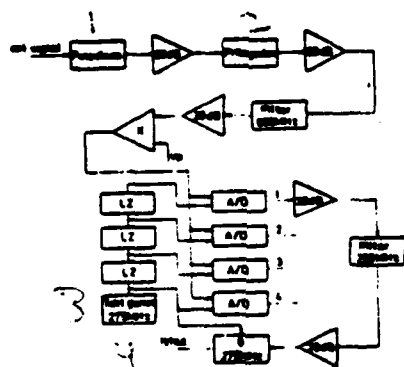


Illustration 15. The structural schema of a low noise optical signal receiver

1. photodiode, 2. adaptor, 3. rhythm generator, 4. exit

A variant of a low noise optical signal receiver, which can receive digital data at speeds up to 1Gbit/s, is presented in illustration 15. Optical systems in which the given receiver is used yield good results (the transmission of TV signals).

The line part of the receiver uses silicon avalanche diodes which are attached to a preamplifier on the base of an FET transistor and has an amplification of around 20 dB, an adaptation part and a low frequency filter to 650 MHz. The avalanche photodiode has a quantum effectiveness up to 50 percent and the response time is less than .3 ns. The receiver's total entrance capacity is less than 3 pF. The entrance resistance of the amplifier amounts to 50 Ω .

The adaptation part reacts only to the front and rear edge of the entrance signal. The signal's amplification and filtering takes place in a very fast comparator (K), where it is transformed into the NRZ code. The comparator represents a thin layer hybrid integral schema with emitter-connection logic (with a delay less than .4 ns).

With the comparator the signal comes into an analog-digital converter (A/D). The rhythmic impulses, which come into the A/D converters, are measured one in relation to another by aid of a maintenance line (LZ). In harmony with this, the measurements are also responses to their exiting. The frequency of the repetition of these rhythmic impulses is 275 MHz.

Regenerators for Optical Communications Systems

In the previous section we considered the process of converting an electrical signal into an optical one (the transmitting part) and then

back, converting the optical signal into an electrical one (the receiving part). This double process occurs in regenerators, only the order is reverse, first the detection of the optical signal is performed, it is then processed onto an electrical level and finally it is again converted into an optical signal.

The regenerator's schema is shown in illustration 16.

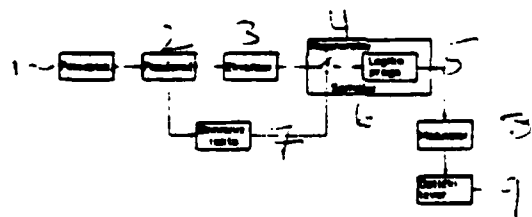


Illustration 16. An optical repeater

1. photodetector, 2. amplifier, 3. equalizer, 4. regenerator, 5. logic threshold, 6. sampler, 7. rhythmic synchronizer, 8. modulator, 9. optical source

As is seen in the illustration, the regenerator is composed of a photodetector, amplifier, corrector, regenerator, modulator and optical emission sources. The signal's processing in the devices attached between the amplifier and modulator is performed analogously to "typical" communications systems. The greatest attention with the regenerator is paid to the low noise entrance amplifier.

It must be mentioned that the possibility of the signal's amplification on the optical level with the stimulation of the light emission exists. Optical regenerators would also operate on this principle, but such a design is still in the testing stage.

The Application of an Optical Data Transmission System

With regard to the advantages which were enumerated at the beginning, optical cable data transmission systems are finding greater and greater application. Many firms from the fields of electronics and telecommunications have also included these systems in their research and production programs. Today, there exists a large number of optical cable transmission lines in the world, either for experimental or commercial purposes. Optical cables are especially well suited for application in urban settings for the connection of various commutation centers in order to achieve the transmission of video signals by means of cable, and for the transmission of data in order to establish communications where electromagnetic disturbances are the greatest.

It must be mentioned that the USA, Japan and Great Britain have gone the farthest in the application of optical cable data transmission. The cost of optical cables, which can be obtained on the open market, fluctuates between 3.5 and 9 dollars per linear meter depending on how many fibers are contained in them (in this case from 6 to 18) and what kind of characteristics the given fibers have.

The Application of Optical Data Transmission Systems for Military Purposes

The application of these systems for military purposes is of special significance, because all their advantages in relation to conventional systems come to special expression here. Optical systems can be used for data transmission in airplanes and ships, with tactical communication systems, under special conditions, etc.

Communications can be achieved over short distances with the use of these systems in airplanes. The systems' following properties come into play here: they are resistant to electromagnetic disturbances, there is no leakage between individual fibers in the optical cable, there is no possibility of short circuiting or sparking, as well as the fact that optical cables are considerably lighter than conventional ones. One example of the use of these systems in military airplanes is the A-7 system found in some airplanes of the American Army. 302 metal conductors are used for the transmission of 115 data signals. When these are replaced by optic fibers, these signals can be transmitted by 13 optic fibers. Because of the wide capacity of the optic fibers, it was possible to multiplex from point to point. The longest optical fiber used here was 10 m. The transmission of digital signals was accomplished at bit speeds of up to 10Mbit/s. A similar transmission system was built into some airplanes of the French Army.

The similar advantages, which characterize these systems used in airplanes, come to fore with their use in ships. The "Little Rock" telephone system developed for the needs of cruisers in the American fleet is an example of their application in fighting ships. Terminals are connected here with an exchange by optical cables 30 m long. This system satisfies requirements for transmission safety and data protection. The utilization of optical data transmission systems on ships also solves the problem of connector damaging. Essentially, electrical cables which are used for digital data transmission are large and stiff, and their transferring in order to maintain terminals connected to the given cables often causes disturbances in the connectors and ultimately their damaging.

Analog optical cable data transmission systems are used to connect anti-submarine sonar to computers for signal processing. One such transmission line can connect 52 parallel channels with a FM capacity of 40 KHz and a dynamic capacity of over 100 dB. This system was

developed by and is utilized in the American Navy. It showed great advantages during testing under realistic conditions.

Optical cable data transmission systems can be applied in a broad class of tactical communications systems, which can be divided into three transmission regions:

- a) short distance (up to 100 m), communications inside a shelter, communications with antennae, transmission of basic data over short distances, etc.,
- b) medium distance (from 100m to 1 km), local network for command locales, data transmission for special weaponry, field computer communications, etc.,
- c) long distance (from 1 to 60 km), data transmission from higher or lower levels, interurban cables, aerial transmission cables, intrabase data transmission, etc.

Illustration 17 can serve as an illustrative example of an optical cable data transmission system used under field conditions.

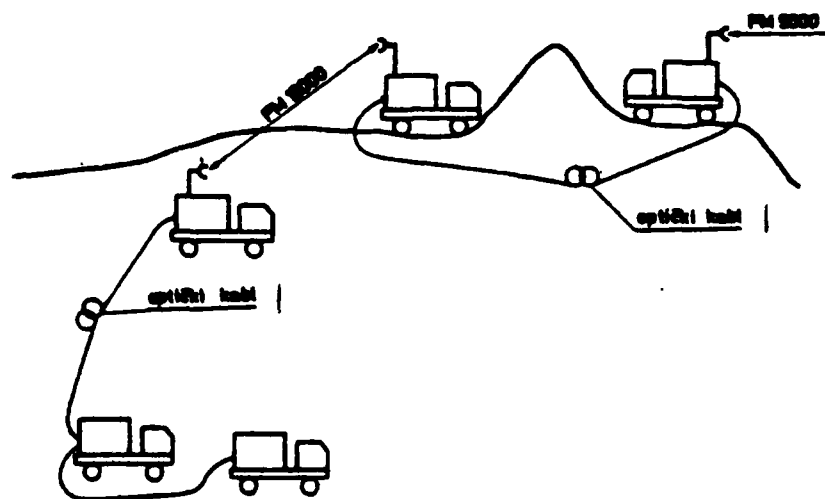


Illustration 17. The application of optical systems under field

conditions

Conclusion

The basic characteristics of fiber-optics data transmission systems, as well as the characteristics of the systems' individual components, have been cited. It has been seen that these systems have some properties in common with conventional metal cable data transmission systems, but are differentiated by a particular approach to their estimation and practical realization. This is due to the existence of an "optical level" in which the signal used is found at a determined moment.

These systems are very perspective and the area of their utilization is very broad. It has already been said that many of them are today found in commercial use. Their usage for military purposes comprises their most significant application.

The further application of optical systems depends on the level of development of optical components with characteristics better than those which exist now, as well as their cost.

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